Oxy-fuel Coal-Fired Combustion
Power Plant System Integration

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Presentation Outline

Introduction: CCS and oxy-fuel combustion

Oxy-fuel advantages and challenges

Retrofit case study for 460 MWe CFB
- Boiler design calculations
- 3D modeling

System improvements for PC and CFB
- Dual firing
- Firing more
- ASU and CPU opportunities

Development roadmap

Conclusions
CO2 Reduction Strategy

Short and medium term approach

- Increase of efficiency provides emission cuts and has a direct impact on the use of natural resources, generation of waste matter and economics.
- Co-firing of solid fossil fuels with CO2 neutral fuels in highly fuel-flexible CFB boilers in repowering and greenfield applications

GHG emission trading systems, emission caps and taxes are expected to lead into demand for solutions to near Zero Emission Power (ZEP) production of fossil fuels
- Retrofits - ZEP ready new plants - greenfield ZEP plants

Long-term approach - Technologies offering potential
- Post-combustion capture
- Pre-combustion capture (IGCC with CO2 separation)
- Oxy-fuel combustion ✐ FW main focus (Oxy-CFB, Oxy-PC)
Alliance to pursue certain projects that will incorporate clean coal technologies and integrated oxy-coal combustion systems into coal-fired electric generating plants to facilitate capture and sequestration of carbon dioxide (CO2).

Validate scale-up of oxy-fuel technology

Improve integration of boiler with ASU and CCS systems
Oxy-Fuel Combustion

- **Air separation**
  - Air \(\rightarrow\) \(N_2, (Ar)\)
  - Flue gas \(\rightarrow\) \(CO_2/H_2O\)

- **Boiler**
  - Coal \(\rightarrow\)
  - Flue gas cleaning

- **Compression Purification**
  - \(CO_2\)

- **Transport Storage**
  - \(H_2O\)

- **Flue gas recycle**
  - to assist in temperature control; can be reduced by adding in-furnace or FB HEX

- **Purity of oxygen is a process optimization issue**

- **Vent gas**
  - \(95-99\% O_2, (Ar, N_2)\)

- **Condensation**
  - Pipeline transport in supercritical phase, \(p>74\) bar (high density, low viscosity)

- **Steam turbine**
  - \(G\)
Oxy-Fuel Technology
Main Advantages

• The established PC/CFB advantages exist also in oxy-combustion.

• Multi-fuel capability in CFB (coal, petroleum coke, lignites etc.)

• Emission control technology, e.g. $\text{SO}_x$ and $\text{NO}_x$ reduction (performed better in oxy-mode)

• Dual-firing capability: Design PC/CFB boiler for both air-firing and oxy-fuel-firing.

Oxy-fuel is considered technically viable. Accurate design and performance prediction are challenging → Current/Future Work:

• Experiments in bench scale and pilot test facilities
• Development and validation of design models
• Long-term demonstration runs
Oxy-Fuel Technology
Challenges

Oxy-fuel gas property increase in:
- gas density
- gas mass flow rate at the same Ug
- gas moisture
- gas thermal capacity, Cp
- energy requirement for Fg*Cp*dT
- energy carryover to HRA
- heat transfer coefficient

- Generated heat per volume is substantially higher than in combustion with air, as O2 concentrations increase
- Adiabatic combustion temperature rises
- Changes in hydrodynamics
- Materials in the high CO_2 and H_2O gas atmosphere
- Emissions prediction
• Balancing of temperature levels by fluegas recycling and firing rate
• Additional balancing of temperature levels by fluidized bed solid mixing in CFB
• FW CFB/INTREX and PC heat surface options available for higher energy absorption
Air-fired CFB reference plant:
- Coal-fired FW SC OTU CFB boiler being constructed in Poland, 460 MWₑ, gross, 439 MWₑ, net, ηₑ, net >43%

Conversion to oxy-fuel firing studied with different design tools
- Aspen Plus® for process system integration
- FW boiler performance design and calculation programs for mass and energy balances, size and heat surfaces etc
3D Modeling

460 MWe Coal-Fired SC OTU CFB Boiler

Outcome: Oxy-CFB with moderate O$_2$ appears technically feasible.
Oxy-CFB Boiler Retrofit Study Layout
Penalty from Oxy-Fuel

Air separation and CO₂ compression require massive amounts of energy...

...resulting in 7-11 %-points lower efficiency, and 25% power derating → More new power plants req’d

Source: Chalmers / Andersson
Maximize component efficiency
- Advanced ST
- Advanced ASU configuration: 3-columns (wait for breakthrough technology)
- Advanced CPU configuration and with use of liquid CO2 pump if applicable

Maximize CO2 capture
- Enhance CO2 recovery by reducing inert gases
- Integration with vent gas recycling and purification

Increase power generation
- Fire-more to get more power (due to increased HTC and LMTD)
- Reduce aux power, and with use of more efficient steam driven compressors

Heat integration
- Recover and integrate low-grade heat for power and efficiency
- Dual-firing boiler for better availability
Process Model
for challenges of integration and optimization

Parameters Studied:
• Dual-firing boiler
• Fire-more concept
• Hot/cold (w/d) recycle
• \( \text{O}_2 \) purity (95 or 99.4%v)
• Air ingress (0 or 3%)
• Heat recovery priority (gases or boiler water)
• \( \text{CO}_2 \) purification on/off
• Compressors driven by extracted steam

- \( \text{CO}_2 > 95\% \)
- Outlet p > 110 bar
Dual (Air/Oxy)-Firing Boiler

Dual-firing for both peak power and CO2 removal
- Air-Firing Mode: max power output for peak power in summer, daytime and weekdays
- Oxy-Firing Mode: low power demand in winter, weekends and overnight
- Potential for Oxy-ready boiler to be supplied before CO2 capture required

Dual-firing for better availability
- Power plant can fired in air-mode with 100% load in case of ASU, CPU, or pipeline trips
Air mode

Flue gas (CO₂, H₂O + O₂, N₂, SO₂ etc.)

Boiler

Drying

Compression

CO₂

Air

ASU

Fuel

Vent

gases

Transport

Storage

H₂ and
soluble
impurities

Condenser

Secondary gas

Fluidizing gas

Mixing

Mixing

Intrex

HP Eco

LP fwph A

LP fwph B

Gas cleaning

HX 1

HX 2

Prim., sec., HP air

Air mode

To stack

Carbon Capture, Storage, and Utilization (CCS) systems involve processes to capture, transport, and store CO₂ from industrial sources. The diagram illustrates a high-level overview of such a system, with flue gas entering and exiting the various components.

1. **Boiler**: The primary source of energy, converting fuel into heat.
2. **Intrex**: Device for removing impurities from the flue gas.
3. **Air preheaters**: Heating the air used in the process.
4. **Mixing**: Combining different streams of gas.
5. **Gas cleaning**: Further purification of the gas.
6. **Condenser**: Where CO₂ is condensed into a liquid form.
7. **Transport Storage**: Temporary storage before CO₂ is transported.
8. **Drying**: Removing moisture from the CO₂.
9. **Compression**: Increasing the pressure of CO₂ for easier transport.

The diagram shows the flow of gases and the interactions between these components, essential for understanding the principles of carbon capture technology.
Oxy mode

Flue gas (CO₂, H₂O + O₂, N₂, SO₂ etc.)

Boiler

Drying

Compression

CO₂

Air

ASU

N₂

Oxygen (96.6% O₂, 3.3% Ar, 0.1% N₂)

Transport Storage

Gas cleaning

Preheater

Mixing

Oxy mode

With optimized gas recycle and heat transfer surface arrangement
Dual-Firing PC 3D Modeling

Optimized amount of gas recycling and firing rate

Air-Fired

Heat Flux (Btu/hr-ft²)

O2-Fired

Air-Fired

Wall Temp. (F)

O2-Fired
3D CFB Modeling
Heat Flux on Furnace Walls

Heat Flux on Furnace Walls

<table>
<thead>
<tr>
<th>Heat Flux [kW/m²]</th>
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<tbody>
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<td>Lower</td>
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<tr>
<td>Higher</td>
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Air-Fired  Oxy-Fired
Firing-More Concept

At the same gas velocity and temperature, the furnace heat transfer coefficient increases in oxy-fuel mode due to flue gas physical properties.

Firing-more to release more heat generates more steam using the same boiler, as a result of enhanced heat transfer coefficient, without increase of furnace temperature.

Fire-more to maintain furnace gas velocity and heat flux.

Extract extra steam from steam turbine to drive CO2 compressors to reduce auxiliary power load.
Fire-More Benefits

Reduces auxiliary power, increase net power
  - Net power reduction: 25% to 10%
  - Specific power penalty reduction: 333 to 126 kWh/tCO2

Allows operation in both air-mode and oxy-mode

Increases CO2 removal
  - CO2 removal: 75 to 106 kg/s

Reduces cost per kW and COE
  - Small increase in CAPEX and OPEX of ASU, CCU, Cooling, and solids handling
  - Same boiler and auxiliaries
Net Specific Power

![Graph showing kWh/tCO2 for different processes and oxygen levels.](image)

- **PC-post**
- **IGCC-pre**
- **PC-oxy Ref[1]**
- **PC-oxy Ref[3]**
- **CFB-FW**

**Legend:**
- **Low O2**
- **High O2**

**Fire-more**
ASU Opportunities & Challenges

- Reduce ASU power by 10%
- Lower ASU capital by 20%
- Heat integration
- Optimum O₂ purity
- Match power plant operation
ASU Power Reduction

Increase thermal integration in distillation system
- Reduces air compression requirements

Reduce $\Delta P_s$
- Compressor intercoolers
- Prepurifier
- Distillation columns

Reduce $\Delta T_s$
- Primary heat exchanger for air cooling
- Cryogenic reboiler-condensers
Advancing Distillation Process

Double Column Cycle

- LP COLUMN
- 10 - 12%
- Less kW

Side Column Cycle

- HP COLUMN
- 7 - 10%
- Less kW

“Oxycoal Cycle”
CO$_2$ Processing Unit (CPU) Opportunities & Challenges

- Meet emissions & CO$_2$ purity regulations
- Integration of compression and purification
- Impact of air ingress
- Condensate treatment and disposal
Compression account for a majority of costs

- CO₂ purity specification will dictate compression
- Cold box process optimization to minimize parasitic power
**CO₂ Purification in Cold Box**

- Min. 95% CO₂
  - One or two stage flash

- 99.9% CO₂
  - Distillation column needed
Roadmap for Oxy-Fuel Technology Development

- **Release of oxycombustion demonstration projects:**
  - Vattenfall / Schwarze Pumpe, 30 MW\textsubscript{th}
  - Total / Lacq, 50 MW\textsubscript{th}

- **Commissioning of Oxy-pilots**

- **Power plant scale demonstration**

- **EU/USA MW-size demos**

- **EU/USA 2nd phase demos**

- **Commercial size power plant**

- **Techno-economic studies**

- **Technology development**

- **General research & development work**

- **Combustion**
  - Emissions
  - Hydrodynamics
  - Materials

- **Feasibility studies**
  - Process studies
  - Cost analyses
  - Market studies
  - Environmental impact studies

- **2000**

- **2003**

- **2006**

- **2009**

- **2012**

- **2015**
Goals of Each Phase of Work

<table>
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<tr>
<th>Goals for each advancing phase of oxycombustion work</th>
<th>R&amp;D Projects</th>
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<th>Demo Scale</th>
<th>Commercial Scale</th>
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When major cuts of CO₂ emissions are required, CCS by oxy-fuel combustion appears technically feasible.

PC and CFB technologies provide flexibility for the design and operation under oxy-combustion conditions.

Experiments carried out so far have indicated good performance. More tests (emissions, heat transfer, materials, fouling...) are needed for further development and validation of design tools & solutions.

Technology demonstrations in fairly large scale and of extended periods are a necessary step when proceeding toward fully commercial size plants.